Extension of the BLT Equation to Incorporate Electromagnetic Field Propagation

Fredrick M. Tesche
Chalmers M. Butler
Holcombe Department of Electrical and Computer Engineering
336 Fluor Daniel EIB
Clemson University, Clemson, SC 29634-0915 USA

This research was supported by the U.S. Department of Defense under MURI grant F49620-01-1-0436 to

University of Illinois at Chicago
and
Clemson University
University of Houston
University of Illinois at Urbana-Champaign
University of Michigan

June 8, 2002

CLEMSON UNIVERSITY

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 2002**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Extension of the BLT Equation to Incorporate Electromagnetic Field Propagation**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Clemson University, Clemson, SC 29634-0915 USA**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
Presentations given at the First Annual Review Meeting on June 8, 2002 DoD MURI Award F49620-01-1-0436, The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**17**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Outline of Presentation

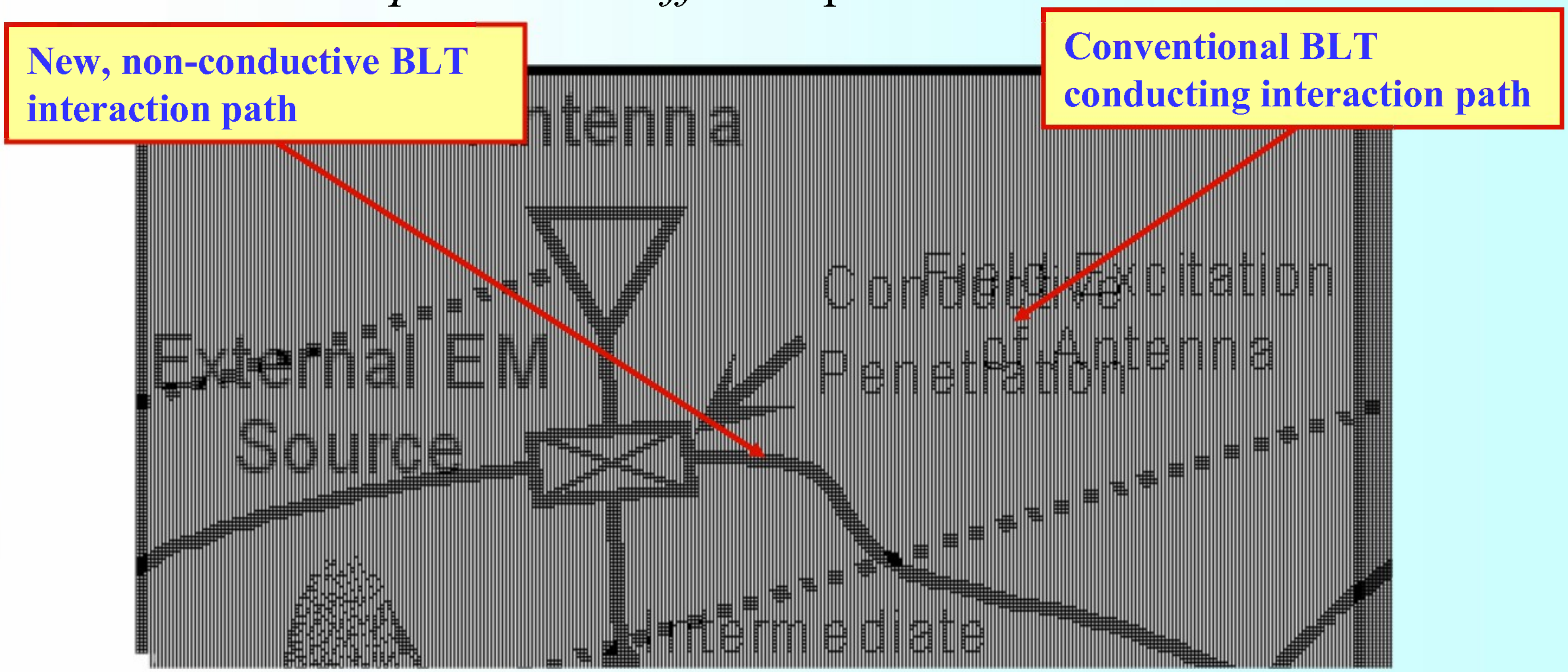
- Introduction
- Review of the Derivation of the BLT Equation
- Extension of the BLT Equation
- Summary

Overview

- The BLT equation for analyzing transmission line networks permits a system-level analysis of the EM effects on large systems
  - This is the basis of the CRIPTE code, and its predecessor, QV7TA
- In this MURI effort, we wish to extend the formulation of the BLT equation to take into account the following:
  - EM field propagation and coupling to the network
  - EM penetration through apertures
  - EM scattering from nearby bodies (including cavities)

Illustration of BLT Equation Extension

- We wish to include <u>non-conducting paths</u> in the interaction sequence diagram
  - To model *aperture* or *diffusive* penetrations



CLEMSON UNIVERSITY

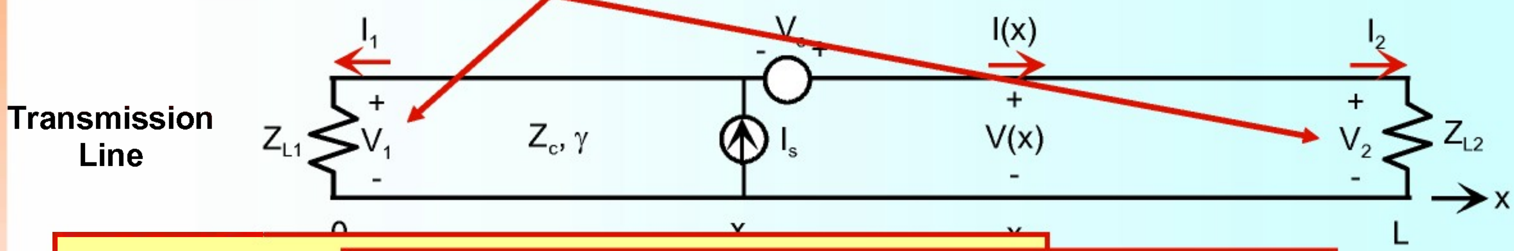
Outline of Presentation

- Motivation
- ***Review of the BLT Equation***
- Extension of the BLT Equation
- Summary

The BLT Equation for a Single Line Network

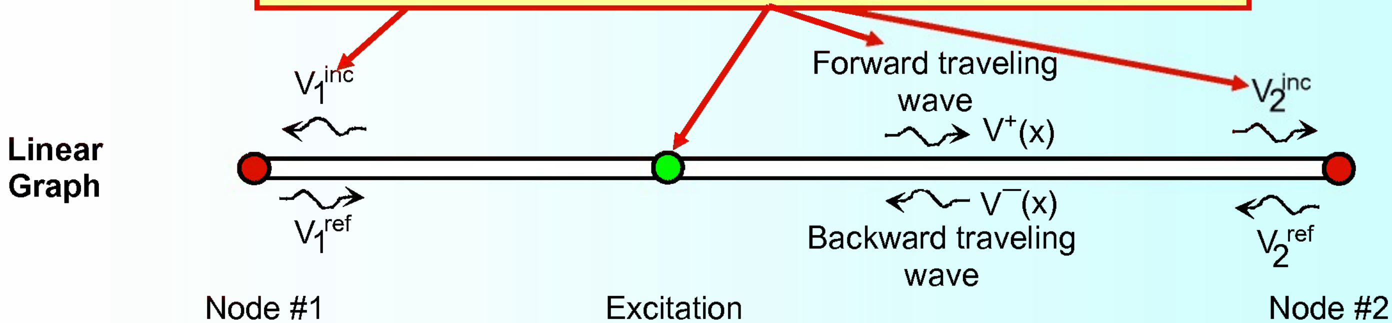
- Consider a single transmission line "network"

The BLT Equation provides the voltage or current responses at the ends (junctions) of the line



This is done by ... incident and r...

And including the excitation of forward and backward traveling wave components on the line by the excitation sources.



The BLT Equation for the Load Voltages

- The BLT equation for the *load voltage responses* is written in a simple matrix form as

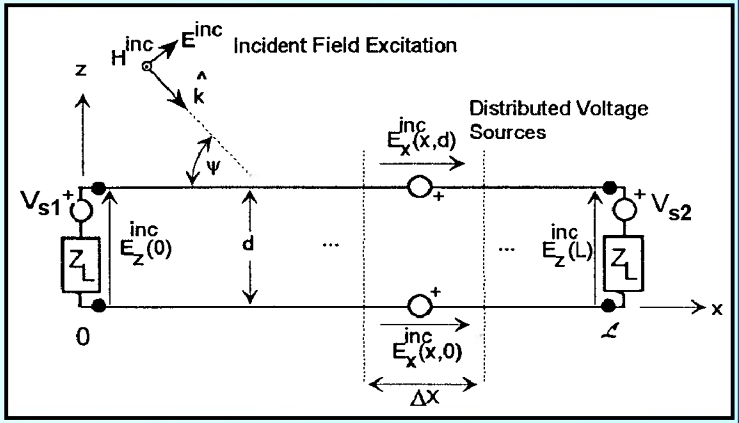
$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} 1+\rho_1 & 0 \\ 0 & 1+\rho_2 \end{bmatrix} \cdot \begin{bmatrix} -\rho_1 & e^{\gamma L} \\ e^{\gamma L} & -\rho_2 \end{bmatrix}^{-1} \cdot \begin{bmatrix} S_1 \\ S_2 \end{bmatrix}$$

- **Load voltages at each end of the line**
- **Matrix involving load reflection coefficients**
- **Inverse matrix involving line propagation**
- **Excitation vector**

  – where the excitation vector for the *lumped* sources is given as

$$\begin{bmatrix} S_1 \\ S_2 \end{bmatrix} = \begin{bmatrix} \frac{1}{2}\left(V_s + Z_c I_s\right) e^{\gamma x_s} \\ -\frac{1}{2}\left(V_s - Z_c I_s\right) e^{\gamma (L - x_s)} \end{bmatrix}$$

The BLT Equation for Incident Field Excitation



- The BLT equation for a lumped voltage source can be viewed as a *Green's function*
  - The response is found by integrating over the line to incorporate the tangential E-field excitation of the line.
- The same functional form of the BLT equation is valid for *incident field* (plane-wave) excitation:

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} 1+\rho_1 & 0 \\ 0 & 1+\rho_2 \end{bmatrix} \cdot \begin{bmatrix} -\rho_1 & e^{\gamma L} \\ e^{\gamma L} & -\rho_2 \end{bmatrix}^{-1} \cdot \begin{bmatrix} S_1 \\ S_2 \end{bmatrix}$$

☞ Only a change in the source vector is necessary:

$$\begin{bmatrix} S_1 \\ S_2 \end{bmatrix} = \frac{E^{inc} d}{2} \begin{bmatrix} \left(e^{jkL(1-\cos\psi)} - 1\right) \\ e^{jkL}\left(e^{-jkL(1+\cos\psi)} - 1\right) \end{bmatrix} \equiv E^{inc} \begin{bmatrix} F_1(\psi) \\ F_2(\psi) \end{bmatrix}$$

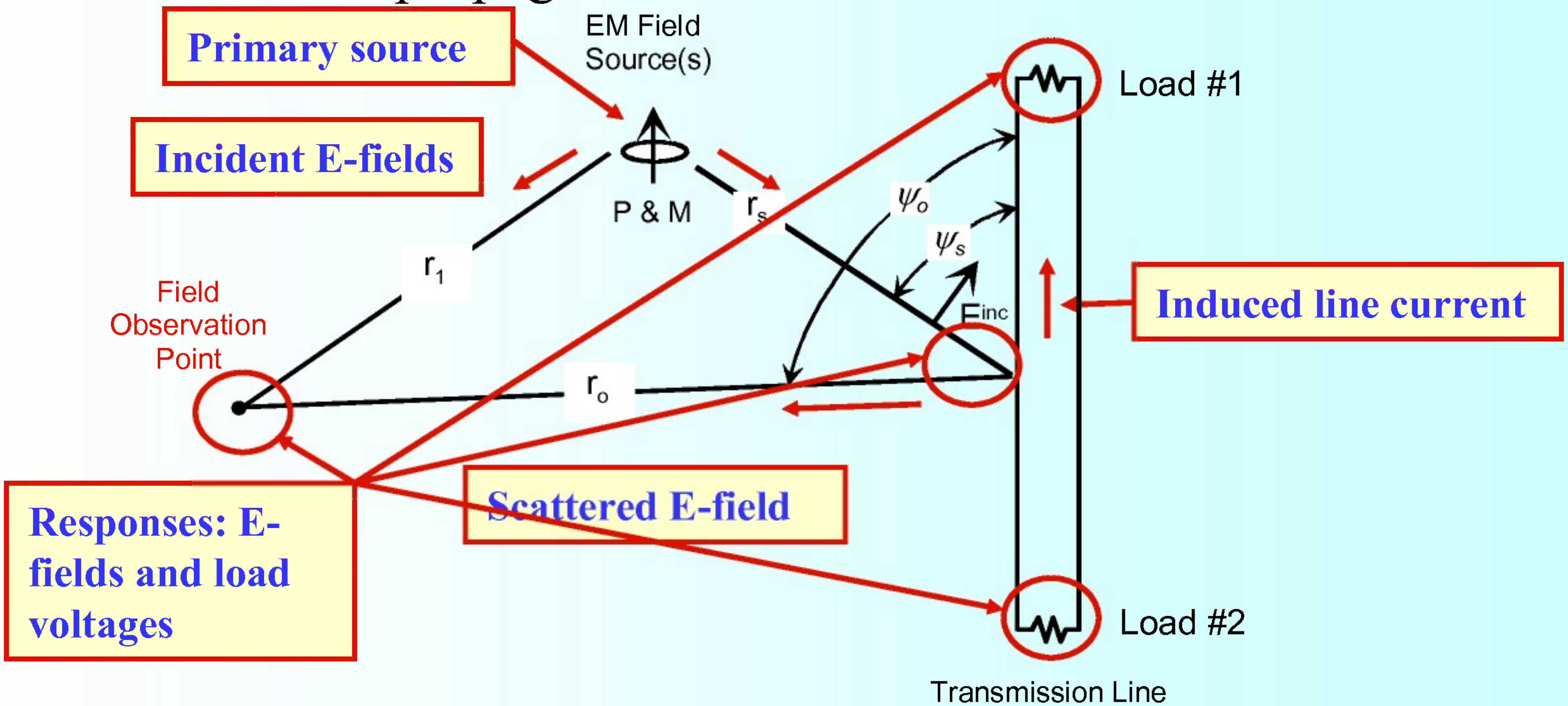
Note the field coupling functions F_1 and F_2

Outline of Presentation

- Motivation
- Review of the Derivation of the BLT Equation
- ***Extension of the BLT Equation***
- Summary

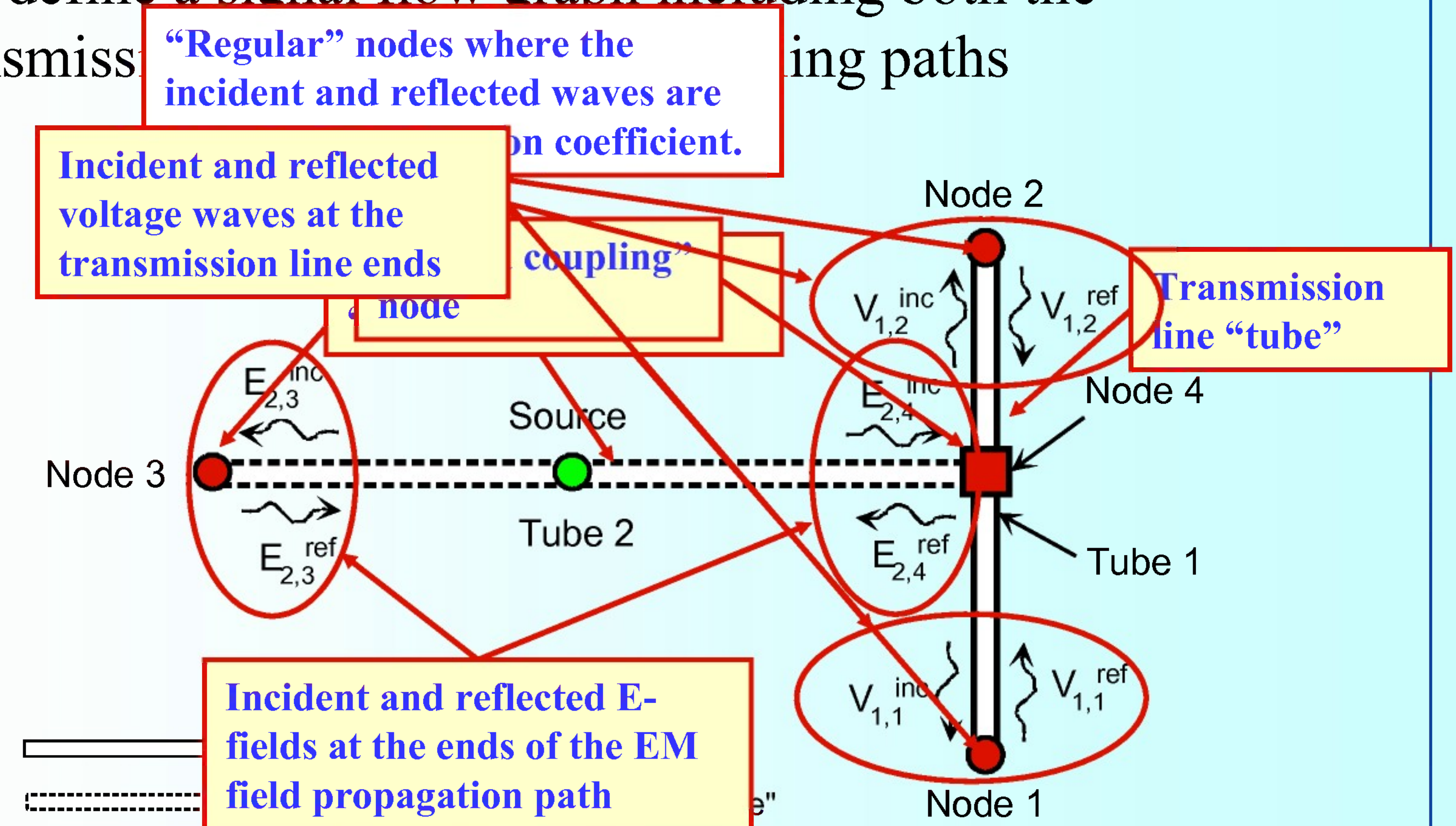
Extension of the BLT Equation to Include EM Field Propagation

- Consider the following simple problem
  - Involving transmission line responses (the "conventional" BLT problem)
  - And EM field propagation from the source to the line



Extension of the BLT Equation (con't.)

- We define a signal flow graph including both the transmiss ing paths



CLEMSON
UNIVERSITY

The Extended BLT Propagation Equation

- As in the case of the transmission line BLT equation, we can define a p... onship between ... and reflected v... malized E-field... tubes:

Transmission line propagation sub-matrix

Field coupling terms between the incident E-field on the line and the traveling voltage waves

Extended BLT Equation

EM field propagation sub-matrix

BLT propagation equation for a single transmission line

$$\begin{bmatrix} V_1^{ref}(0) \\ V_2^{ref}(0) \end{bmatrix} = \begin{bmatrix} 0 & e^{\gamma L} \\ e^{\gamma L} & 0 \end{bmatrix} \cdot \begin{bmatrix} V_1^{inc}(0) \\ V_2^{inc}(0) \end{bmatrix} + \begin{bmatrix} -\frac{1}{2}(V_s + Z_c I_s)e^{\gamma x_s} \\ +\frac{1}{2}(V_s - Z_c I_s)e^{\gamma(L-x_s)} \end{bmatrix}$$

Note that the E-fields are normalized by suitable lengths a_3 and a_4, which are typical dimensions of the nodes

...that both the coupling and ...ation terms contain the sa... functions F_1 and F_2 --- a conse... of reciprocity

4-vector of incident voltage waves on the tubes

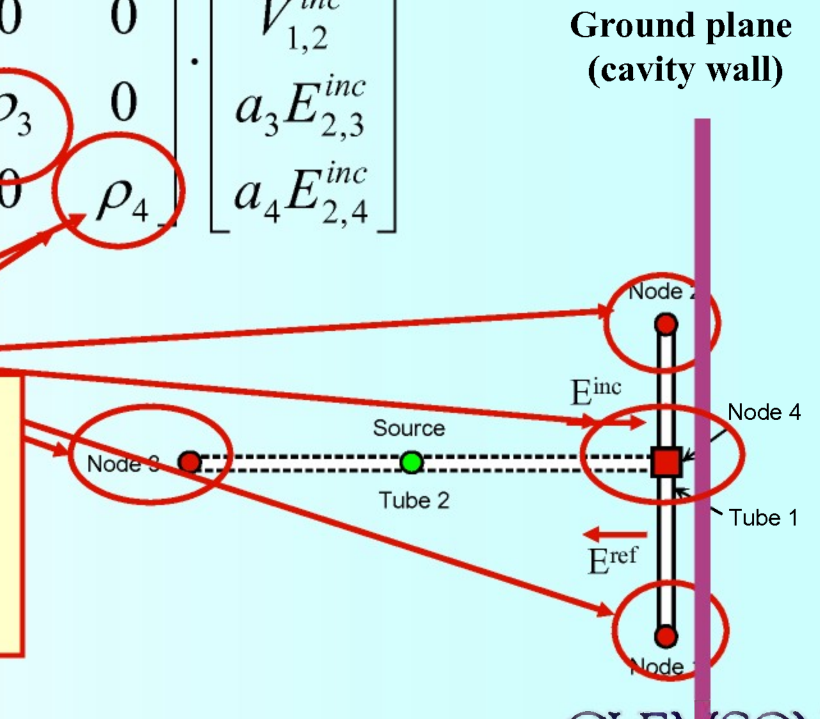
...ith the source functions

CLEMSON UNIVERSITY

The Extended BLT Reflection Coefficient Matrix

- Similarly, we define an *extended* reflection coefficient matrix, which is similar to the 2x2 matrix for the simple transmission line:

$$\begin{bmatrix} V_{1,1}^{ref} \\ V_{1,2}^{ref} \\ a_3 E_{2,3}^{ref} \\ a_4 E_{2,4}^{ref} \end{bmatrix} = \begin{bmatrix} \rho_1 & 0 & 0 & 0 \\ 0 & \rho_2 & 0 & 0 \\ 0 & 0 & \rho_3 & 0 \\ 0 & 0 & 0 & \rho_4 \end{bmatrix} \cdot \begin{bmatrix} V_{1,1}^{inc} \\ V_{1,2}^{inc} \\ a_3 E_{2,3}^{inc} \\ a_4 E_{2,4}^{inc} \end{bmatrix}$$



ρ_3 … that
re … wall
us … the

ρ_4 (which = 0 in this example) corresponds to E-field reflection at node 4, in the absence of the transmission line. The line has already been taken into account in the propagation and coupling matrix.

The Extended Voltage BLT Equation

- The BLT reflection and propagation matrix equations can be combined just like the single transmission line case to yield the *extended* BLT equation for the load voltages and normalized E-fields:

$$\begin{bmatrix} V_{1,1} \\ V_{1,2} \\ a_3 E_{2,3} \\ a_4 E_{2,4} \end{bmatrix} = \begin{bmatrix} 1+\rho_1 & 0 & 0 & 0 \\ 0 & 1+\rho_2 & 0 & 0 \\ 0 & 0 & 1+\rho_3 & 0 \\ 0 & 0 & 0 & 1+\rho_4 \end{bmatrix} \cdot \begin{bmatrix} -\rho_1 & e^{\gamma L} & 0 & -\dfrac{1}{a_4} F_1(\psi) \\ e^{\gamma L} & -\rho_2 & 0 & -\dfrac{1}{a_4} F_2(\psi) \\ 0 & 0 & -\rho_3 & \dfrac{r_o}{a_3} e^{jkr_o} \\ -\dfrac{jk}{2\pi a_4}\dfrac{Z_o}{Z_c} F_1(\psi_o) & -\dfrac{jk}{2\pi a_4}\dfrac{Z_o}{Z_c} F_2(\psi_o) & \dfrac{r_o}{a_4} e^{jkr_o} & -\rho_4 \end{bmatrix}^{-1} \cdot \begin{bmatrix} 0 \\ 0 \\ S_1(\psi_s)\dfrac{r_o e^{jk(r_o - r_s)}}{r_s} \\ S_2(\psi_1)\dfrac{r_o e^{jl(r_o - r_1)}}{r_1} \end{bmatrix}$$

BLT voltage equation for a single transmission line

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} 1+\rho_1 & 0 \\ 0 & 1+\rho_2 \end{bmatrix} \cdot \begin{bmatrix} -\rho_1 & e^{\gamma L} \\ e^{\gamma L} & -\rho_2 \end{bmatrix}^{-1} \begin{bmatrix} S_1 \\ S_2 \end{bmatrix}$$

The extended BLT voltage equation

CLEMSON UNIVERSITY

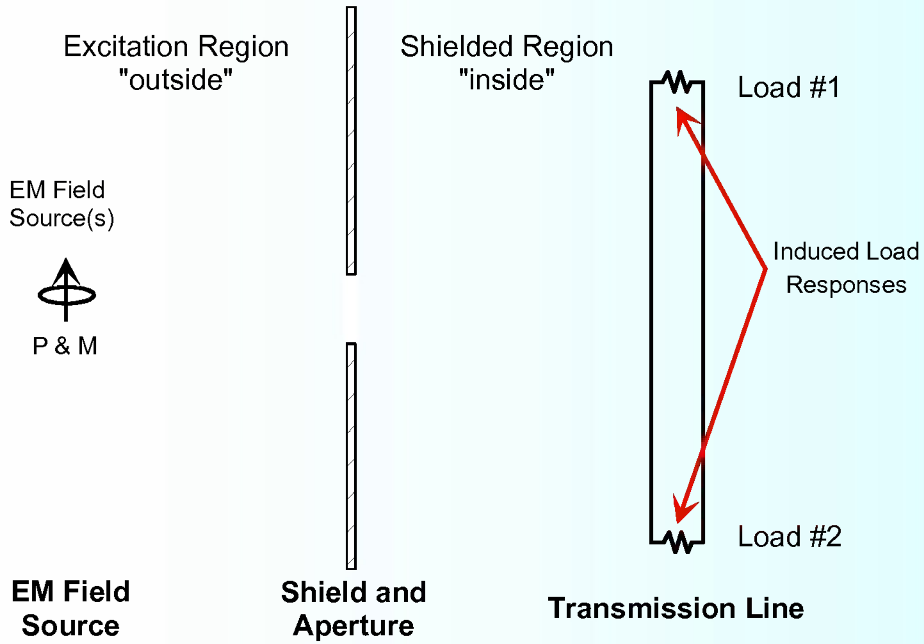
Outline of Presentation

- Motivation
- Review of the Derivation of the BLT Equation
- Extension of the BLT Equation
- ***Summary***

Summary

- A modified BLT equation, taking into account EM field propagation paths in addition to the usual transmission line propagation mechanisms, has been developed.
  - This required modifying the BLT propagation matrix to include the field coupling to the transmission line and the EM scattering from the line.
  - These features have been illustrated with a very simple example.
- The next step in this development will be to include the more general case of EM shields with apertures, and multiple field paths, as shown in the next slide …….

Work Currently Underway …



Transmission line within a simple shielded region with an aperture

Interaction diagram, showing both field propagation and transmission line propagation paths